♠INAF – TURIN ASTROPHYSICAL OBSERVATORY
♡UNIVERSITY OF ROME “TOR VERGATA”
Department of Physics

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The diversity of Neptune-sized exoplanets

L. Naponiello ♠, L. Mancini ♡, A. S. Bonomo♠, M. Damasso♠, M. Pinamonti♠, A. Sozzetti♠
♠luca.naponiello@inaf.it ♡lmancini@roma2.infn.it

Introduction

Neptune-sized planets ($3\,R_{\oplus} \lesssim R_{\rm p} \lesssim 6\,R_{\oplus}$) are compelling targets for atmospheric characterization. While the atmospheres of larger planets have been sufficiently explored by HST and JWST, the formation and evolution of these intermediate-sized planets remain poorly understood due to their limited sample size and diverse characteristics.

Exo-Neptunes encompass a range of compositions, including both gaseous and high-density planets with significant rocky fractions, like TOI-1853 b [1], TOI-332 b [2], and TOI-849 b [3].

At short orbital periods ($P_{\rm orb} \lesssim 5$ days), there exists a well-known “desert” of Neptunes (Fig. 2). This paucity may be attributed to formation and migration processes or atmospheric escape phenomena. Indeed, observations of a few warm Neptunes, such as GJ 436 b and GJ 3470 b, indicate ongoing atmospheric loss, suggesting that they are planets in transition [4]. Observing the atmospheres of planets inside and close to the *Neptune desert* offers then a clear way to disentangle between all the different hypotheses.

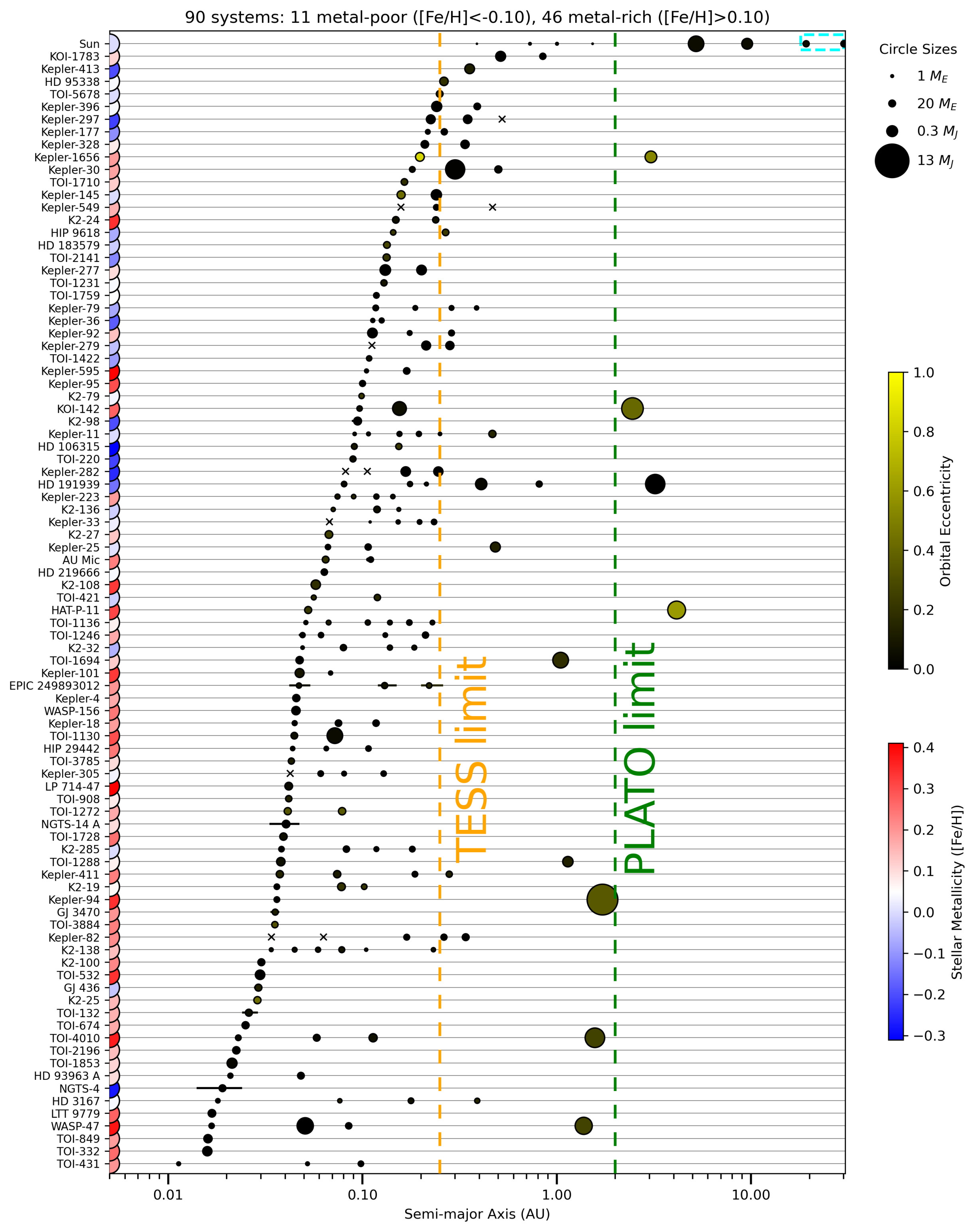

Figure 1: The architecture of all planetary systems hosting at least one Neptune-sized planet with the mass determined at $3\,\sigma$ precision. Transiting planets marked with × have no mass estimations yet. Of the 129 Neptune-sized planets listed here, 57 have $a < 0.1$ au and 72 have $a > 0.1$ au.

Obtaining well-constrained orbital and physical parameters of new Neptune-sized planets, especially as a function of stellar properties, is mandatory in order to:

- investigate their prevailing formation and migration mechanisms (e.g. disk-driven or high-eccentricity migration - HEM) and how they differ from the other planets;
- compare their mass-radius relationship with the other planets, and to explore the reasons behind their great diversity of bulk densities (core/compositions);
- constrain the limits of the hot-Neptune desert (Fig. 2) and understand its origin.

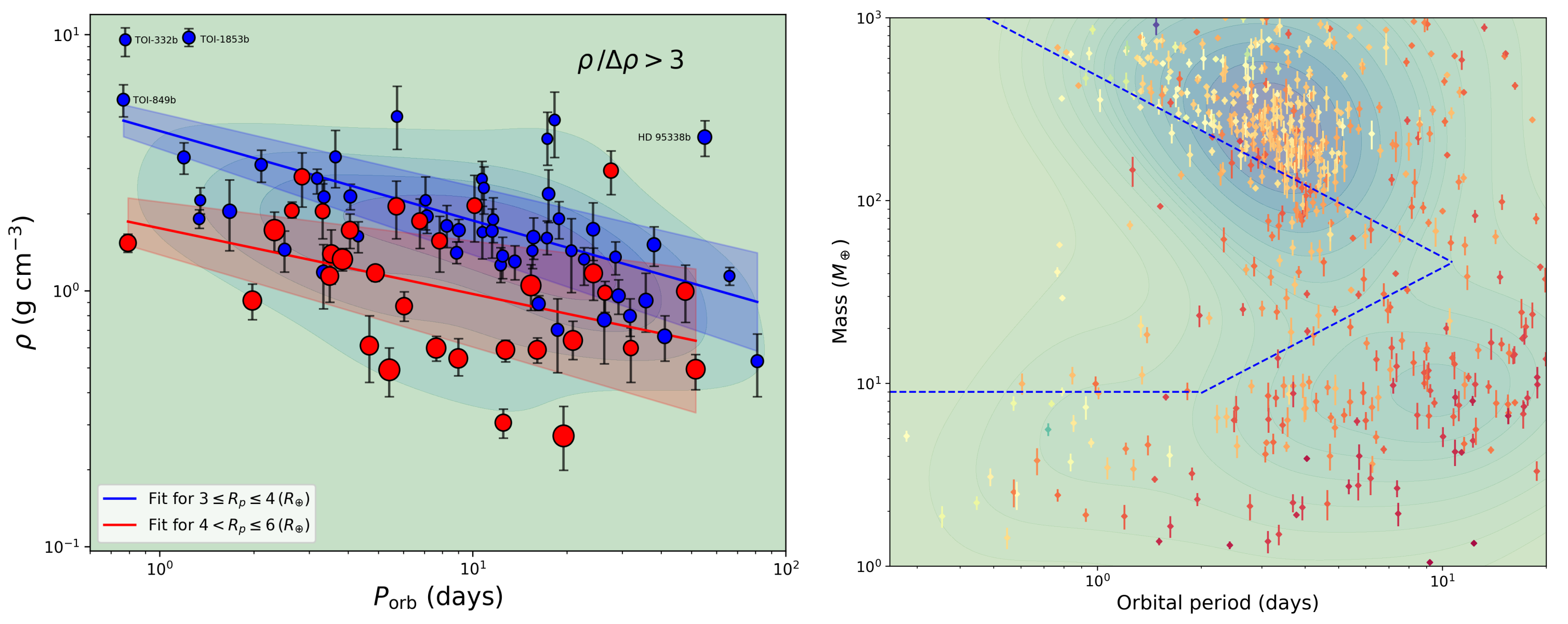

Figure 2: *Left-hand panel:* the density distribution over the orbital period of the current well-characterized Neptune-size sample. *Right-hand panel:* The Neptune desert is here delimited by dashed blue lines (from Deeg et al., A&A 677, 2023 and Mazeh et al., A&A 589, 2016). Only the exoplanets with high precision on the density have been plotted.

The results of the GAPS HARPS-N Neptune program

Within the Global Architecture of Planetary System (GAPS) project, we ran a three-year observational program to follow-up TESS candidates, which lead to the discovery of four Neptune-sized exoplanets (TOI-1710 b, TOI-1422 b [5], TOI-1853 b, TOI-5076 b), and more about to be published (Fig. 3).

Among them, an especially noteworthy discovery is that of **TOI-1853 b** [1], which boasts a radius of $3.46 \pm 0.08\,R_{\oplus}$, a mass of $73.2 \pm 2.7\,M_{\oplus}$, and an extraordinarily high bulk density of $9.7 \pm 0.8\,{\rm g\,cm^{-3}}$, which is nearly twice that of the Earth.

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The physical properties of **TOI-1853 b** cannot be explained with the core accretion formation model alone, as they necessitate the exploration of alternative migration/evolution models in order to explain the assembly of its exceptionally heavy core (i.e. a *catastrophic origin* that may result from either multiple planetary impacts or HEM followed by severe tidal dissipation). The discovery of this super-massive planet highlights the imperative need to further investigate the parameter space occupied by Neptune-type worlds, as each new discovery has the potential to yield remarkable surprises and insights.

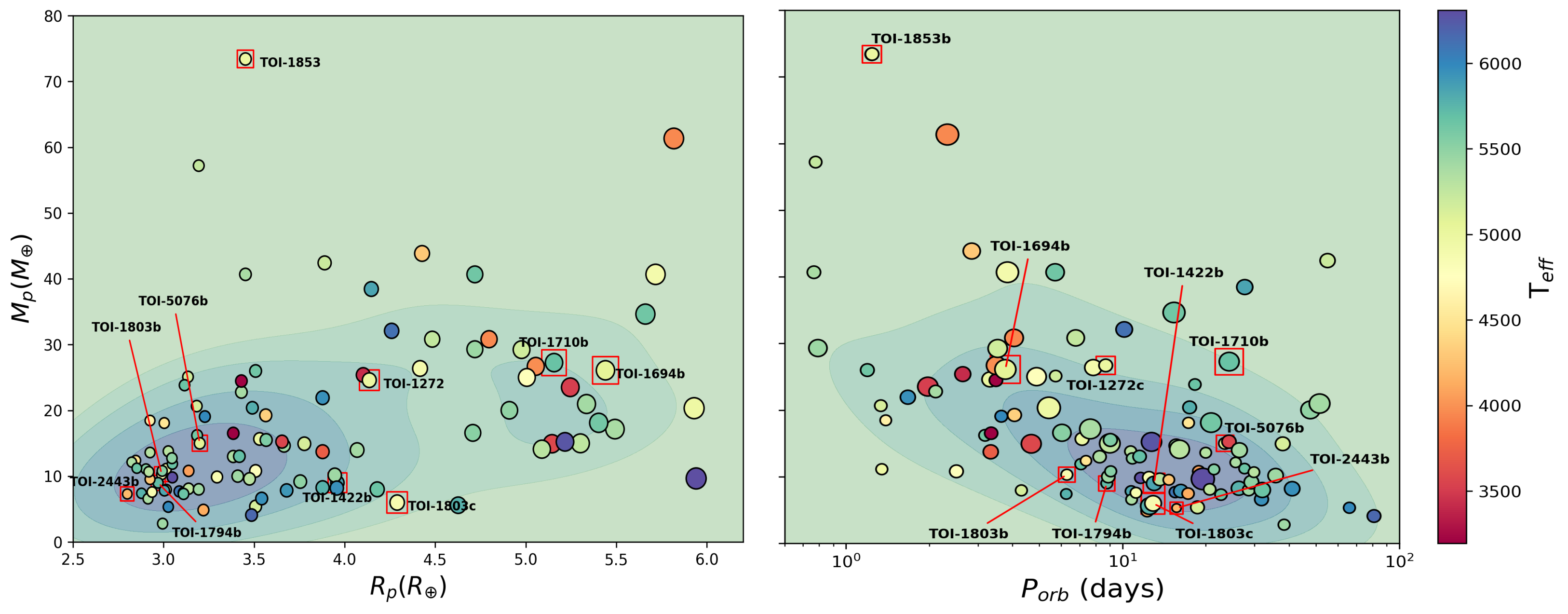

Figure 3: *Left-hand panel:* the mass distribution over the planetary radii of the current well-characterized Neptune-size sample. *Right-hand panel:* the mass distribution over orbital period of the same sample. The targets monitored during the GAPS program are highlighted by red boxes [1, 5]. The size of the circles is proportional to the radius of the planets.

A few trends are starting to emerge. For instance, as the orbital period increases, the bulk density of Neptune-sized planets exhibits a linear decrease in log-log space (Fig. 2). This trend is evident even for planets larger than Neptune, which exhibit lower densities on average, as expected. The escalating photo-evaporation effect could provide a possible explanation for most of these objects, since planets on shorter orbital periods receive elevated levels of X-UV radiation. However, the most dense exo-Neptunes cannot be explained using photo-evaporation models [1, 2]. At the same time, most of these planets orbit around metal-rich stars (Fig. 1), especially those with semi-major axis below ≈ 0.1 au, while planets of metal-poor star systems appear to form at greater distances from their stars (> 0.1 au).

The novel Neptune program

The TESS mission continues to reveal new Neptune candidates. Many of these are excellent targets for atmospheric characterization, as the majority of TOIs are bright.

We are, therefore, continuing our observational program to follow-up TESS candidates and enlarge the number of the known Neptune-sized planets.

Our aim is to measure the masses of these candidates to a precision of 20% as this is the requirement for robust planetary atmospheric characterization with the JWST.

We have selected and started observing a set of a dozen new TESS candidates that

- have already been vetted by ground-based photometry, low-resolution spectroscopy and high-resolution imaging;
- are optimum targets for two of the best high-precision velocimeters, i.e. HARPS and HARPS-N.

References

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